GAIN OF THE GYROTRON WITH HIGH CIRCULAR WAVEGUIDE MODE (WHISPERING GALLERY MODE)

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One of two Russian efforts to increase gyrotron output power has been to experiment with oscillator devices utilizing high order resonator modes, particularly the whispering gallery modes. We present the result of design analyses for this case and some design parameters will be given at the end. The potential application of whispering gallery modes in the solid-state gyrotron is also briefly described.

Background

Remarkable power capability and efficiency for gyrotron devices have been exhibited recently in the Soviet Union[1,2] and in the United States.[3,4] Its wide potential applications in plasma fusion, radar, communications and ECM will depend upon the development of improved electron guns and efficient circuit structures. The phase bunching mechanism plays an important role in the gyrotron and this same mechanism could be utilized in the solid state gyrotron[5] in the near future.

Here we will discuss design characteristics of an efficient high power circuit. When the electron gun becomes space charge limited and the perveance increases, the electron beam quality deteriorates and the efficiency and output power are consequently reduced. Up to this limit, the gyrotron with TE°_{11} mode operation is one of the best candidates for the high power operation.[6] Beyond this limit, one has to make use of a larger interaction circuit with a high azimuthal mode, i.e., whispering gallery mode. Indeed an output power of 380 kW was achieved at 15 GHz with 30% efficiency[6] for operation in the TE_{911} resonator mode. Whenever possible mode competition can be avoided, it will be profitable to exploit this whispering gallery mode for high power and high efficiency operation. The same is true for the case of the solid-state gyrotron that uses the bunching mechanism, and not mere population inversion mechamism by the optical pumping.

Whispering Gallery Modes

The highest linear gain in the gyrotron has been known to be achieved with the TE°_{11} mode.[7] The optimized maximum gain in this case is $0.056\ f/\beta_z$ (dB/cm), where f is the frequency in GHz and β_z the axial electron velocity divided by the vacuum light speed. For low perveance operation, the TE°_{11} mode gyrotron provides the highest overall gain with the trochoidal beam configuration. However, utilization of an annular helical type beam does not significantly reduce the linear gain very much.

The limitation in achieving high perveance with the trochoidal beam geometry will require interaction with a larger circuit. The transverse electric fields of the TE_{91} and TE_{52} modes (Fig. 1) show a clear advantage for possible strong interaction between the beam and electric field when the beam is located near the peak electric field region. It is possible to determine the growth rates of the TE_{911}, TE_{521}, etc. cavity modes at the fundamental cyclotron harmonic mode by making use of the rigorous dispersion equation.[7] We obtain the optimized growth rate in the cavity individually (Fig. 2) under the situation of no mode competition in order to show the strength of individual interaction with the electron beam. Indeed all unwanted modes were able to be removed[6] by introducing a thin tapered center rod (Fig. 3). When we use the beam location marked in Fig. 4, we can achieve relatively high linear gain with a TE_{91} mode, i.e., $0.02\ f/\beta_z$ (dB/cm).

Application to Solid-State Gyrotron

The plasma current inside a solid state medium has been well studied and documented. The current state of crystal impurity of InSb, for instance, can provide enough electron beam flow to produce significant power at 245 GHz.[5] To enhance the cavity output power we can make use of the whispering gallery mode concept. An annular strip of metal or p-type InSb could play the role of cathode when it is attached to the n-type InSb to generate an electron beam inside the medium. The radius of the annular ring should be 75 to 85% of the cavity radius. Output power can be extracted by means of a very thin center rod that does not contact with the cavity crystal. This will avoid mode competition in the cavity.

Conclusion

The whispering gallery mode, when the mode competition is eliminated by a coax tapered metal, (center rod) can provide high power at efficiency that can be greater than 40% with optimum selection of circuit parameters. Output power levels near 200 kW could be expected for operating parameters near 9.5 Amp, 71 kV, 35 GHz and $v_\perp/v_z = 1.5$.

References

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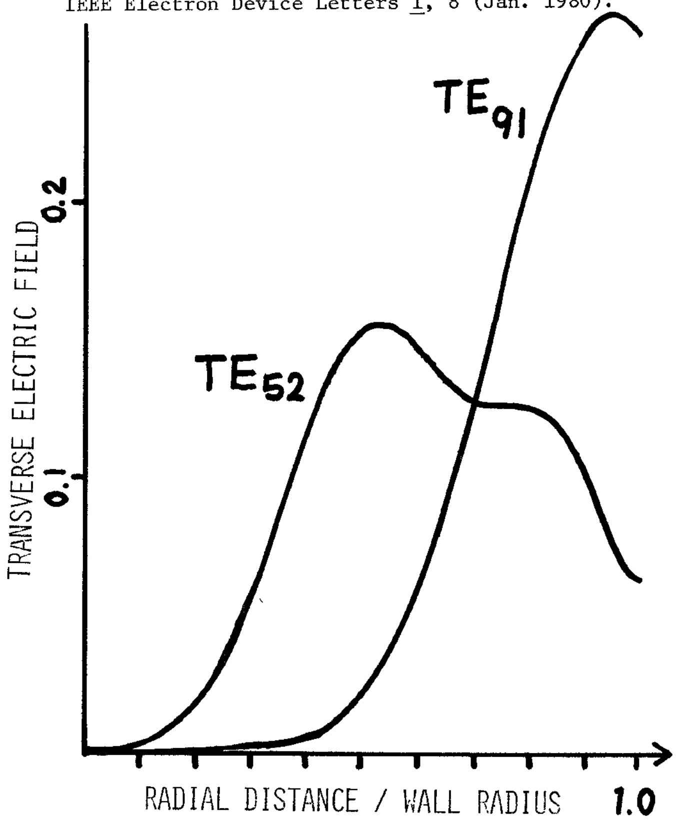

Fig. 1. Transverse electric field (scalar magnitude) vs. the radial distance divided by the waveguide radius. The field is not normalized and the scale of the vertical axis is arbitrary. The TE_{91} mode has a high energy density (proportional to the square of vertical height in the graph) near the waveguide wall.

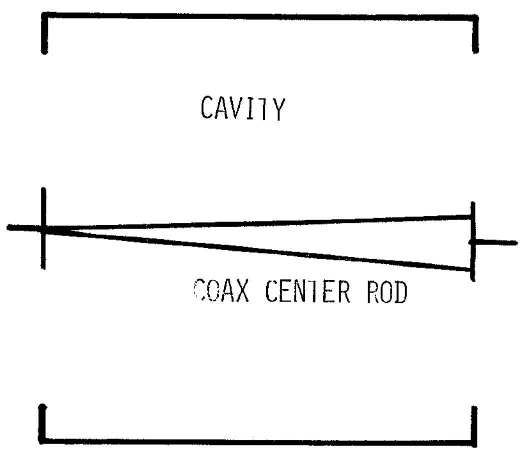

Fig. 3. Gyrotron oscillator cavity with a coax metal cylinder (a center rod). The center rod can be a thin metal rod or a conic shape as shown here.

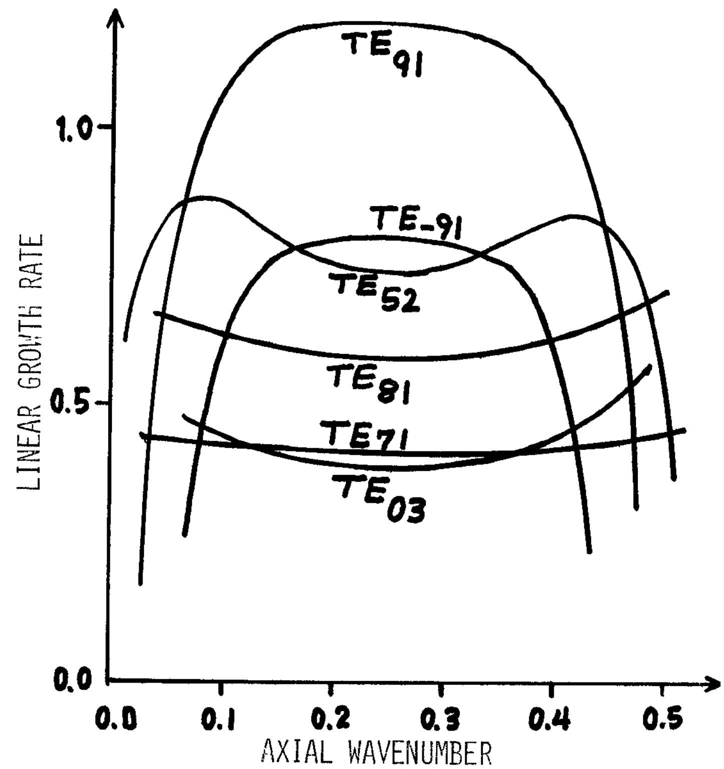

Fig. 2. Relative linear growth rates vs. axial wave number for different modes near the TE_{91} modes (optimized). In the case of our design example in which 71 kV, 9.5 Amp $v_{\perp}/v_z = 1.5$ wall radius 0.54 cm and Larmor radius 0.061 cm are used at 35 GHz, the vertical axis should be multiplied by 2.2 dB/cm and the horizontal axis by 7.33/cm.

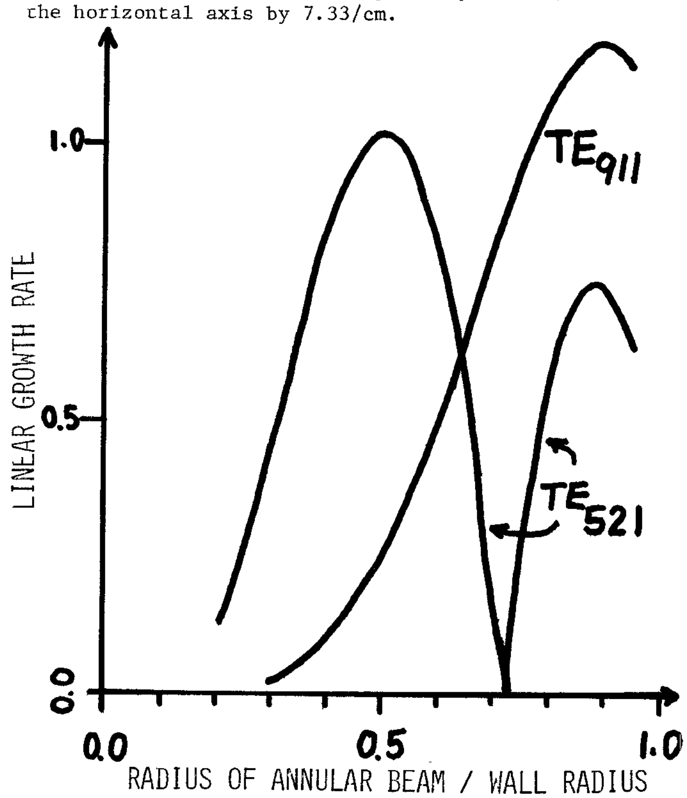

Fig. 4. Relative linear growth rates vs. the radius of beam center divided by the wall radius at the same circuit parameters with those in Fig. 2. Notice that the growth rate of TE_{911} mode is far more dominant than that of TE_{521} for the radius ratio greater than 0.7.